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Computer simulation and flume tank testing of scale engineering models: How well do these techniques predict full-scale at-sea performance of bottom trawls?

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ABSTRACT

A Canadian demersal survey trawl (Campelen 1800) was used to investigate the differences in trawl geometry and resistance using dynamic simulation, flume tank testing, and full-scale at-sea observations. A dynamic simulation of the trawl was evaluated using DynamiT software. A 1:10 scale model was built and tested in a flume tank at the Fisheries and Marine Institute of Memorial University of Newfoundland (Canada). Full-scale observations of the Campelen 1800 in action were collected during the 2011 fall multi-species survey aboard the research vessel *CCGS Teleost*. The numerical and physical modelling data were assessed to determine their ability to predict full-scale at sea performance of the Campelen 1800 trawl. The numerical simulation data were also compared against scale model engineering performance under identical conditions. The study demonstrates that the ideal method with which to accurately predict full-scale at-sea performance of bottom trawls or used for designing a trawling system probably does not exist. Therefore, the importance of using two or three complementary tools should be encouraged as an ideal process for designing a trawling system and/or assisting the gear development circle.

1. Introduction

The method by which new fishing gears are designed and tested has dramatically changed and become more advanced and sophisticated over the last few decades. The major reasons for this continuing development in methodological process are rooted in the high cost of evaluating new gear designs at sea together with impressive improvements in the predictive abilities of computer simulation and physical models, both of which have been shown to reduce relevant expenses and potential risks for gear manufacturers and researchers (Winger et al., 2006; Prat et al., 2008; Queirolo et al., 2009). The driving forces of increasing regulations, bycatch restrictions, and concerns over ecosystem impact of bottom trawls have also been cited for significant improvements in the way new fishing gears are designed and tested (Winger et al., 2006).

The cycle of gear development proposed today should include the use of computer simulation, physical model testing, and at-sea evaluations in a complementary manner and in a logical sequence of work, as the ideal process for designing a new fishing gear system (Winger et al., 2006). Most importantly, the use of computer-based numerical modelling and simulation is encouraged during the early stages of design for validating simple design ideas, as a fast and convenient method. The recent rise in commercially available trawl design and simulation software has significantly improved the speed and quality of design work. Today, several commercial software packages are available for purchase and use on desktop computers and tablets (e.g., DynamiT, SimuTrawl, Trawl Vision Designer and Trawl Vision Simulator, CadTrawl, and CATS). Most of these software packages have the ability to simulate the effects of different materials and design features on trawl shape and performance under different rigging and towing scenarios, as well as calculate expected mechanical stresses on the seafloor (e.g., Vincent, 2000; Queirolo et al., 2009). By comparison, testing physical models in a flume tank, which is considered the *de facto* standard for evaluating new designs and forms the backbone of the modern fishing gear development cycle (Winger et al., 2006), is recommended in order to validate simulated values derived in previous simulation work (Queirolo et al., 2009). Benefits attributed to constructing and testing physical models include the ability to (1) explore potential defects in design; (2) examine the effect of

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alterations in design and rigging; (3) examine the effect of speed and rigging changes on gear geometry and orientation; (4) measure forces acting on the gear; and (5) measure motions of fishing gear (see discussions by Dickson, 1959; Fridman, 1986; Winger et al., 2006). Finally, evaluation of full-scale prototypes at sea is always necessary for assessing the real fishing gear performance and identifying the most successful design features and trawl components of the new fishing gear system. The accuracy of measuring and predicting trawl geometry and performance of a new gear design plays an important role in gear development process. In real fishing conditions, trawl geometry and performance can vary from tow to tow and may be affected by various factors (e.g., towing speeds, water currents, bottom type) and increasing error in accuracy of measurements. The use of acoustic trawl monitoring sensors (e.g., SCANMAR acoustic trawl monitoring instruments) have permitted researchers to improve their monitoring of trawl performance at sea, identify any gear malfunctions and reduce variability in trawl geometry and performance (see, for example, Walsh and McCallum, 1995, 1997).

Given the high cost of evaluating new gear designs at sea, many trawl designers/researchers and manufacturers proceed with computer simulation followed by the testing of physical scale models in flume tanks. However, some might be tempted to speculate whether computer simulation might someday replace physical models or others could raise a question about how well do computer simulation and physical modelling predict full-scale gear performance at sea? Interestingly, few studies have been conducted to evaluate the accuracy/precision of numerical and physical modelling techniques in the comparison with full-scale trawl performance during the last decade. In some cases, data from physical models have been compared to full-scale trawls (e.g. Morse et al., 1992; Fiorentini et al., 1991, 1992, 2004; Sala et al., 2009), and in other cases data from computer simulations have been compared to physical models (e.g., Queirolo et al., 2009), but no clear studies exist in which all three techniques are compared, or any comparison between software, or between flume tanks. Hence, this study represents a unique and novel piece of research.

The objective of this study was to assess the accuracy of computer simulation and physical modelling approaches in predicting the full-scale at-sea performance (geometry and resistance) of the Campelen 1800 trawl. In addition, this study also investigated the ability of computer simulation to predict performance of physical models. The results are discussed in relation to the commonly used methodological approach for fishing gear design described by Winger et al. (2006).

2. Materials and methods

2.1. Trawl design and scale engineering model specifications

The Campelen 1800 was selected as the trawl design for this study. This is the standard demersal survey trawl widely used by Fisheries and Oceans Canada on the east coast of Canada since 1995, replacing earlier versions of the Engel 145 otter trawl and the Yankee 41 shrimp trawl (Walsh and McCallum, 1997). This trawl design is known as a four panel design with cut-away lower wings and is rigged with three bridles and 4.3 m^2, 1400 kg Morgère Polyvalent trawl doors. The Campelen 1800 trawl is rigged with a 35.6 m rockhopper footgear and uses 356 mm diameter rubber disks. Trawl construction is of 4.0, 3.0 and 2.0 mm diameter polyethylene twine varying in mesh size from 80 mm in the wings to 60 mm in the square and the first bellies and 44 mm in the remaining bellies, extension and codend (see Fig. 1 for details). The design has changed very little over time as a result of stringent standardization of construction and operational protocols (Walsh et al., 2009).

A linear scale of 1:10 was selected as the best balance between the limitations of the test facility (i.e., flume tank size), objectives of the test programme, and the ability to extrapolate model results to full-scale performance. The majority of the components were custom ordered and/or fabricated in-house and the model was assembled by hand using standard trawl construction practices (see Winger et al., 2006).

2.2. Dynamic simulation tests

Trawl simulation software (i.e., DynamiT) developed by the French Research Institute for the Exploitation of the Sea (IFREMER) was utilized to simulate the mechanical behaviour of the Campelen 1800 trawl. The software has the ability to calculate and simulate the dynamic behaviour of virtually any trawl type, commonly referred to as dynamic simulation (Vincent, 2000; Queirolo et al., 2009). For this study, the simulations were performed for different door spreads, depths, and towing speeds. Output parameters included door spread, wing-end spread, headline height, and towing resistance (i.e., warp/bridle tension).

In order to facilitate comparison to the physical modelling, the dynamic simulations were conducted at the same door spreads as the flume tank tests in order to eliminate bias in trawl performance when comparing the two datasets. The simulations were constrained for the desired door spreads by deploying the appropriate warp and simply attaching a rope of diameter 0.0 mm between the trawl doors as a restrictor rope (referred to as restrictor rope based simulation). Specifically, we conducted a series of dynamic simulations for six different door spreads of 45.0, 50.0, 55.0, 60.0, 65.0, and 70.0 m at four different towing speeds of 2.0, 2.5, 3.0 and 3.5 knots. The trawl geometry parameters (i.e., wing-end spread, headline height) and resistance (i.e., bridle tension) of each combination of treatments were obtained.

To facilitate comparison with the full-scale observations of the Campelen 1800 trawl, the dynamic simulations were performed at a standardized towing speed of 3.0 knots and varying towing depths or we simply replicated all the tows as conducted aboard the *CCGS Teleost* during the 2011 fall multi-species survey (referred to as depth based simulation). The trawl geometry parameters (i.e., door spread, wing-end spread, headline height) and resistance (i.e., warp tension) of each combination of treatments were documented.

2.3. Flume tank tests

A 1:10 scale model was constructed by the Fisheries and Marine Institute of Memorial University of Newfoundland using mainly Froude scaling principals (Tauti, 1934; Dickson, 1959; Fridman, 1973; Hu et al., 2001). The scaled model was constructed in a manner that approximates the geometric, kinematic, dynamic, and force laws of full-scale trawls. The modelling laws may be summarized as:

$$\lambda = \frac{L_f}{L_m} \tag{1}$$

$$A_m = \frac{A_f}{\lambda^2} \tag{2}$$

$$F_m = \frac{F_f}{\lambda^3}\frac{\rho_m}{\rho_f} \tag{3}$$

where L, A, F and ρ are length, area, force and water density, the subscripts m and f refer to model and full-scale, respectively. To compensate for differences with respect to the full-scale trawl due to available twine diameter, an area scale and force scale are also used. The velocity scale is given by:

$$\lambda^{1/2} = \frac{v_f}{v_m} \tag{4}$$

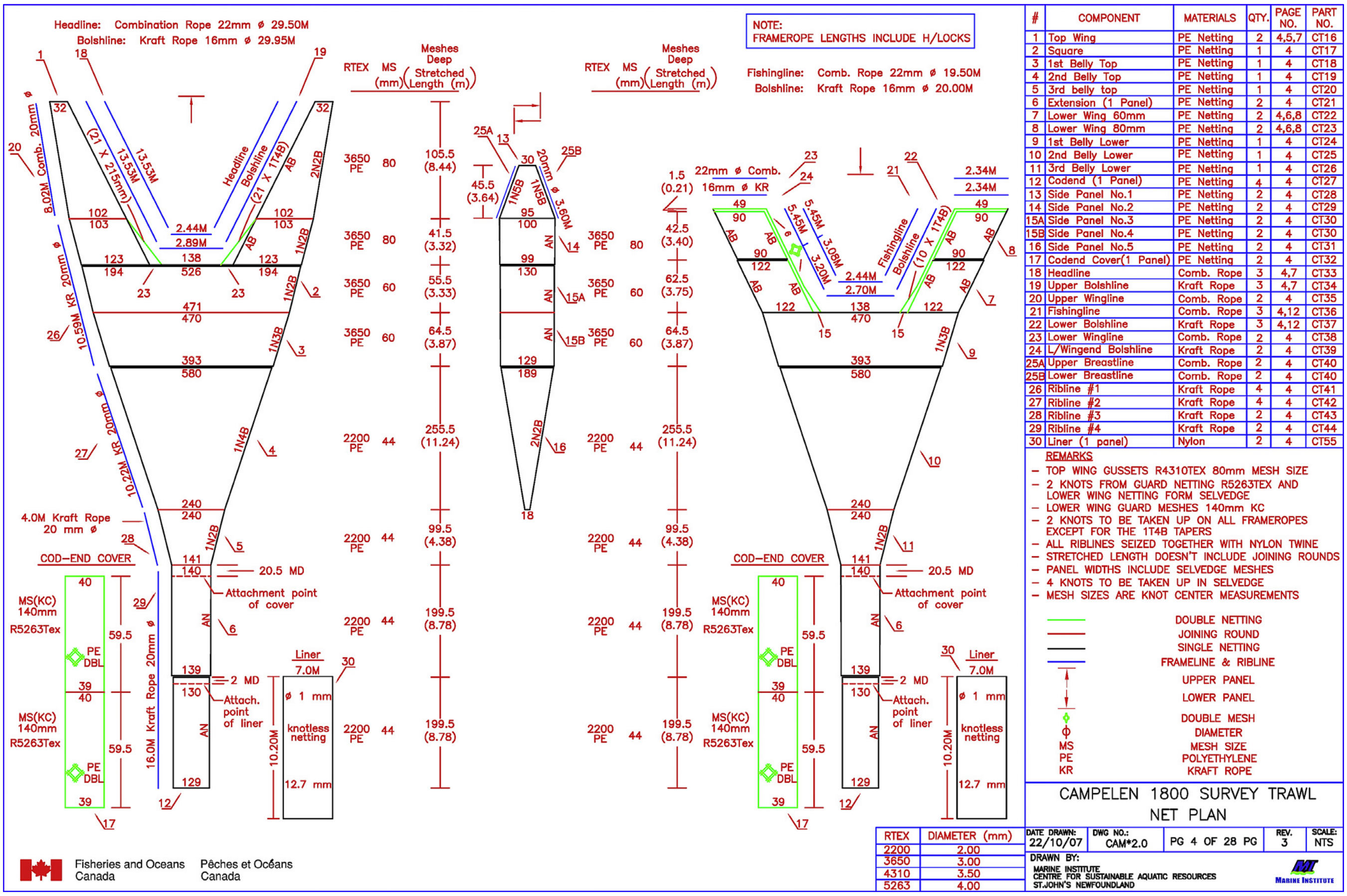

Fig. 1. Schematic netplan of the Campelen 1800 demersal survey trawl. See Walsh et al. (2009) for additional drawings.

where v is the towing speed.

Similar scaling theory has been applied by previous researchers for designing and testing the physical performance of trawl models in flume tanks (for details, see Morse et al., 1992; Fiorentini et al., 2004; Sala et al., 2009; Queirolo et al., 2009).

To examine the performance of the scale physical model, the 1:10 model was deployed and tested at the Fisheries and Marine Institute's flume tank, located at the Centre for Sustainable Aquatic Resources (Memorial University of Newfoundland), where different towing speeds and rigging scenarios (i.e., door spreads) were assessed.

The experiments were conducted by connecting the trawl's bridles directly to the flume tank masts. In this case, the measurements were carried out at six different mast spreads (corresponding to full-scale door spreads of 45.0, 50.0, 55.0, 60.0, 65.0, and 70.0 m) and at four different towing speeds through water (corresponding to the full-scale range of 2.0, 2.5, 3.0 and 3.5 knots). For statistical comparison purposes, the physical modelling tests were repeated five times for each experimental scenario (120 runs). Estimates of the hydrodynamic performance of the model (e.g., wing-end spread, headline height, bridle tension-load ahead of the bridles) for each experimental combination of treatments ($n = 120$) were measured and recorded using the existing optical and data acquisition systems within the flume tank.

2.4. Evaluation of the full-scale prototype

Full-scale observations of the Campelen 1800 trawl in action were collected during the fall of 2011 aboard the research vessel *CCGS Teleost*. Trip 1 was conducted during September 01–08, 2011 to collect data related to towing resistance, in which observations of trawl geometry and shaft torque were collected at two speeds (3.0 and 3.5 knots speed over ground) and seven depths (250, 500, 750, 1000, 1250, 1500, and 1600 m). Using a series of well developed relationships, these data were used to develop estimates of total thrust for the different depths (see Gardner, 2012 for more details). This dataset was used for the purpose of comparing full-scale observations against estimates of trawl resistance (i.e., warp tension) obtained by the dynamic simulation under the same trawling conditions (i.e., towing depths and speeds).

Trip 2 was conducted during November 29–December 09, 2011 as part of the fall multi-species survey aboard the same vessel. This included 48 tows at a standardized speed of 3.0 knots (speed over ground) and varying depths as determined by the survey design.

The data related to trawl depth, headline height/trawl opening, door spread, and wing-end spread were obtained using SCANMAR hydroacoustic trawl monitoring sensors attached to the fishing gear (e.g., door spread sensors are placed on each trawl door, wing spread sensors are positioned on each of the upper wing tips, depth and opening/height sensors are attached on the centre of headline). Such data were automatically logged at 5 s intervals using the NAFC (Northwest Atlantic Fisheries Centre) SeaTrawl data acquisition software. At each fishing station, the scope ratio (trawl warp length divided by fishing depth) was prescribed according to the Scope Ratio Table (Walsh and McCallum, 1997) which helps to achieve and maintain stable bottom contact of the trawl doors during towing.

2.5. Data analysis

The data regarding trawl geometry and resistance of the Campelen 1800 trawl obtained from the dynamic simulation, physical

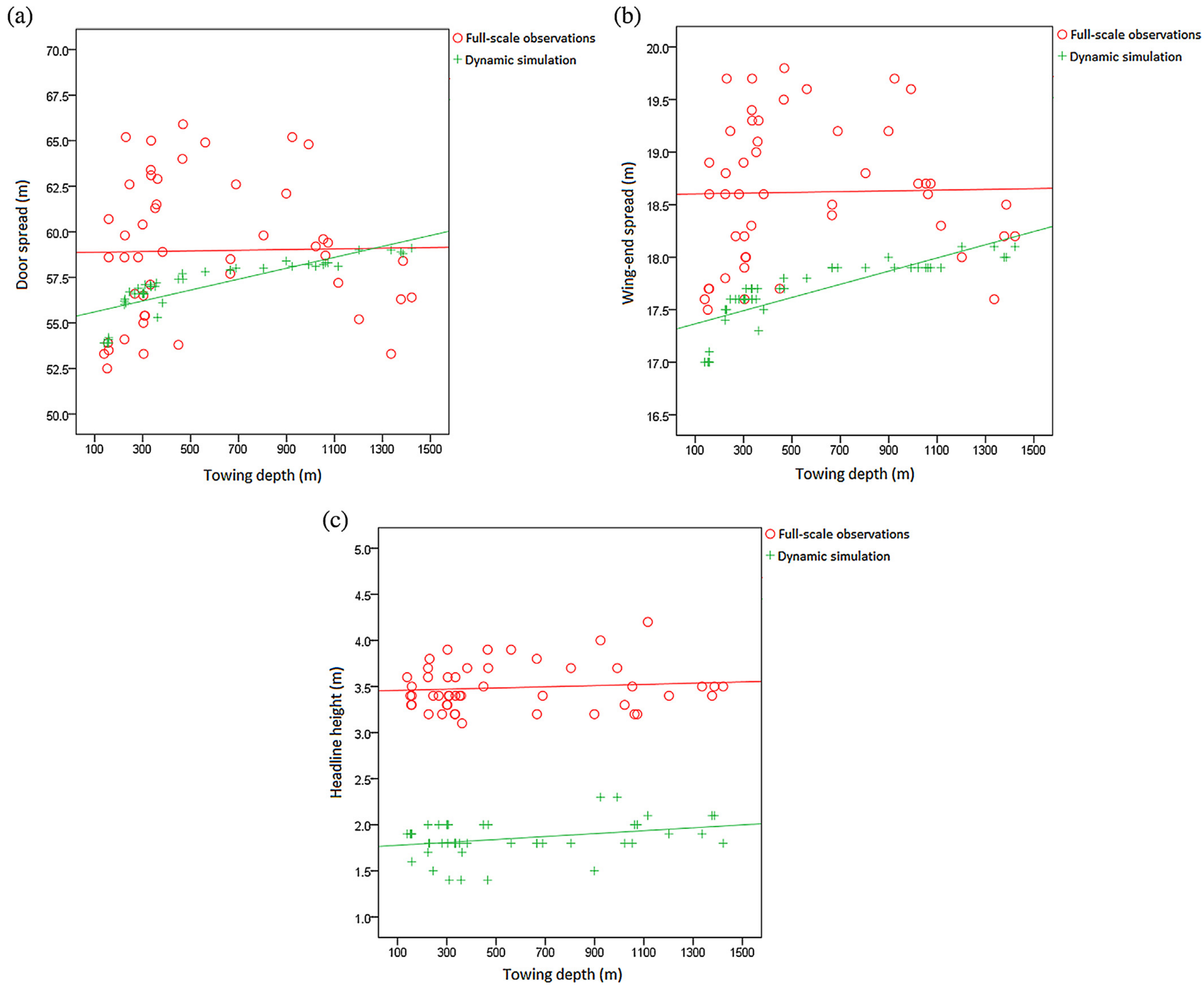

Fig. 2. Relationships observed between door spread and towing depth (a); wing spread and towing depth (b); and headline height and towing depth (c). The plots show the experimental data collected with dynamic simulation (plus), full-scale observations at sea (open circle). The best fit regression lines are shown each scatter plot.

modelling, and evaluation of the full-scale trawl were analyzed to investigate differences in trawl geometry and resistance separately based on each technique. In our first analysis, the dynamic simulations and physical modelling datasets were compared against the full-scale at sea performance of the Campelen 1800 trawl. In our second analysis, the dynamic simulation data were compared against the predictions of the 1:10 scale flume tank model when tested under the same conditions.

The hypotheses that dynamic simulation and physical modelling accurately predict full-scale performance and secondly that dynamic simulation accurately predict physical modelling were statistically tested, requiring either parametric or non-parametric statistical test depending on the degree of homogeneity of variance within the datasets. To this end, the Analysis of Covariance (ANCOVA) and Kruskal–Wallis One Way Analysis of Variance were found to be appropriate statistical approaches to investigate these hypotheses. In addition, linear regressions and ANOVA's were also applied to describe relationships in engineering trawl performance and compare slopes among different methods (dynamic simulation vs. physical modelling vs. at-sea observations). All of the statistical procedures were performed using the IBM SPSS Statistics software package.

Different relationships that describe the mechanical behaviour of the Campelen 1800 trawl were examined including (1) door spread and towing depth, (2) wing-end spread and towing depth, (3) headline height and towing depth, (4) door spread and wing spread, (5) door spread and headline height, (6) towing depth and warp tension, (7) door spread and bridle tension, and (8) towing speed and bridle tension.

3. Results

3.1. Comparison between dynamic simulation and at-sea observations

At sea observations of full-scale trawl performance revealed no obvious trend in either door spread or wing spread in relation to towing depth (Fig. 2a and b). By comparison, dynamic simulation predicted increasing door spread and wing-end spread with increasing towing depth. The regression analysis indicates that the towing depth explained 66% and 67% of the variation in door spread and wing-end spread for the dynamic simulation, respectively.

Wing-end spread showed a predictable relationship with door spread for both depth based dynamic simulation and full-scale

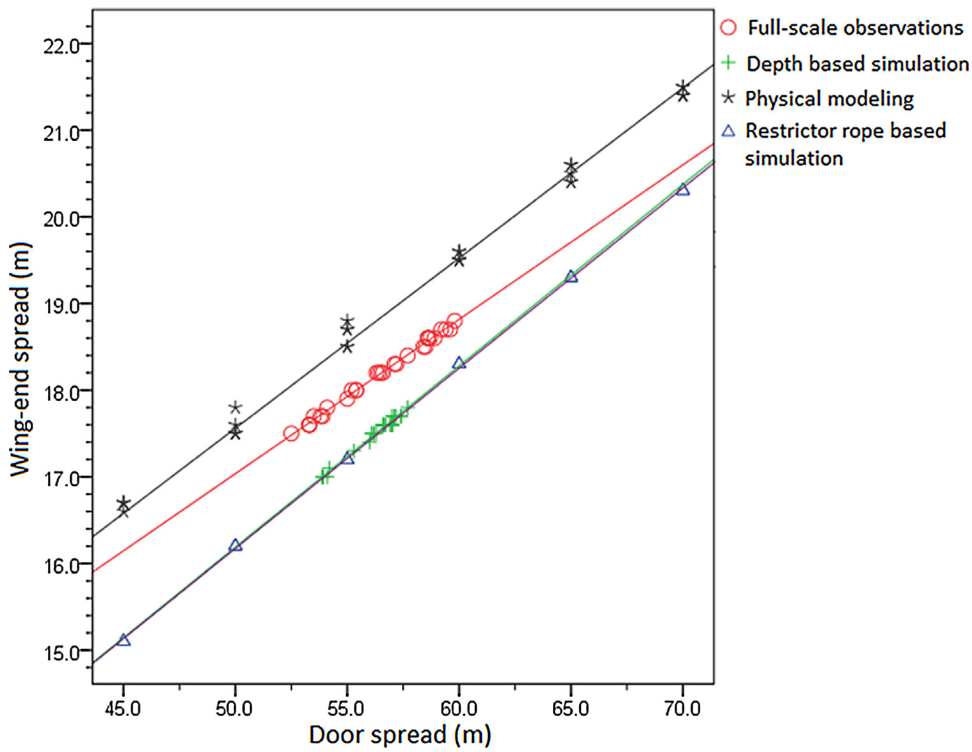

Fig. 3. Relationships observed between wing-end spread with respect to door spread. The plots show the experimental data collected with depth based dynamic simulation (plus), full-scale observations at sea (open circle), restrictor rope based dynamic simulation (triangle), and physical modelling (star). The best fit regression lines are shown each scatter plot.

observations (Fig. 3). The slopes of the relationships in the two methods were not significantly different ($p > 0.05$). The regression model explained the variation in wing-end spread due to changes in door spread, with 98.9% and 99.8% from dynamic simulations and full-scale observations, respectively. The predictions of door spread and wing-end spread provided by the dynamic simulations were within 5% of the values observed by the full-scale at-sea performance (see Table 1 for details), but these differences were statistically significant ($p < 0.05$, Kruskal Wallis test).

Headline height of the trawl showed little relationship with towing depth (Fig. 2c). Both the dynamic simulation and full-scale observations showed little trend (positive or negative) over the depth ranges that were evaluated. Headline height of the trawl was predicted to decrease with increasing door spread according to the depth based dynamic simulation (Fig. 4). By comparison, our full-scale observations at-sea revealed little relationship between headline height and door spread. The variation in headline height was not properly explained by door spread and towing depth in both cases. The predictions of headline height provided by dynamic simulations were significantly lower than full-scale at-sea observations ($p < 0.001$, ANCOVA test), averaging 1.6 m or approximately 46% less than full-scale at-sea observations (see Table 1).

Warp tension showed an increase with towing depth in both dynamic simulation and full-scale observations, but with different slopes in each case (Fig. 5). Regression model results indicate that

Table 1
Summary statistics of trawl geometry and resistance parameters for the Campelen 1800 shrimp trawl under towing speed of 3.0 knots.

Evaluation method	Variable	*N*	Mean	STDEV	Min.	Max.
Restrictor rope based simulation (i.e., *door spreads were constrained at desired distances*)	Door spread (m)	6	57.5	9.4	45.0	70.0
	Wing spread (m)	6	17.0	1.9	15.1	20.3
	Headline height (m)	6	2.0	0.5	1.4	2.8
	Bridle tension (MT.)	30	5.6	0.6	5.0	6.6
Depth based simulation (i.e., *replicated the survey tows*)	Towing depth (m)	48	559.7	396.9	139.0	1422.0
	Door spread (m)	48	57.0	1.4	53.9	59.1
	Wing spread (m)	48	17.7	0.3	17.0	18.1
	Headline height (m)	48	1.9	0.2	1.4	2.3
	Warp tension (MT.)	6	9.9	1.5	7.8	11.5
Physical modelling (i.e., *door spreads were constrained at desired distances*)	Door spread (m)	30	57.5	8.6	45.0	70.0
	Wing spread (m)	30	19.0	1.7	15.8	21.5
	Headline height (m)	30	4.1	0.5	3.5	4.9
	Bridle tension (MT.)	30	5.8	0.1	5.6	6.1
Full-scale observations (*2011 fall multi-species survey aboard the CCGS Teleost*)	Towing depth (m)	48	559.7	396.9	139.0	1422.0
	Door spread (m)	48	59.0	3.9	52.5	65.9
	Wing spread (m)	48	18.6	0.7	17.3	19.8
	Headline height (m)	48	3.5	0.2	3.1	4.2
	Warp tension (MT.)	6	14.3	2.3	11.0	16.9

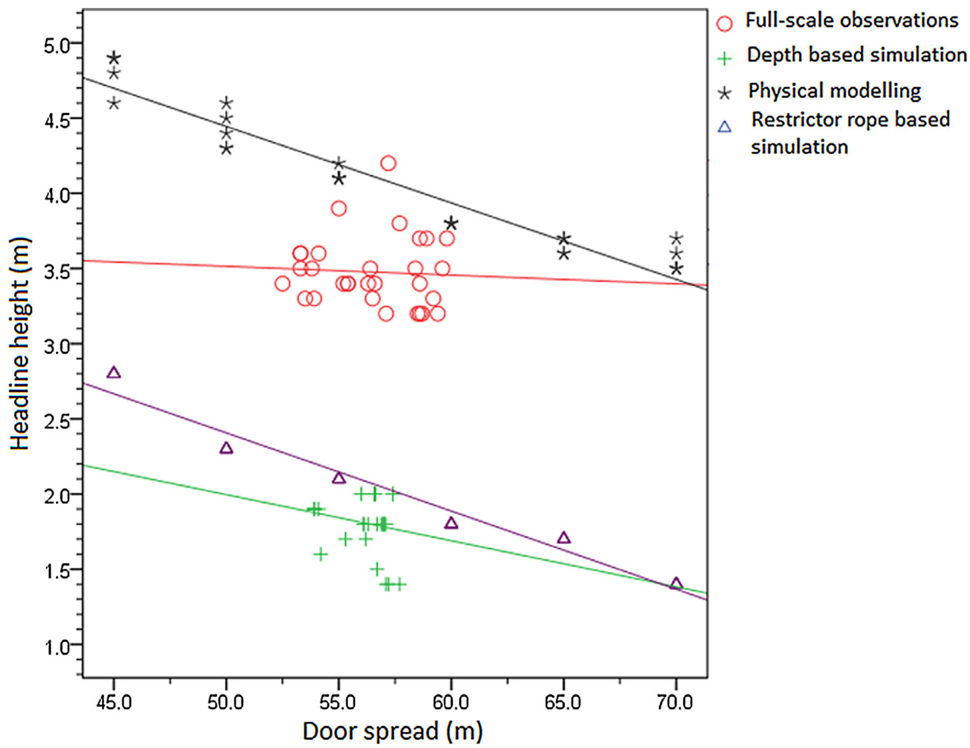

Fig. 4. Relationships observed between headline height with respect to door spread. The plots show the experimental data collected with depth based dynamic simulation (plus), full-scale observations at sea (open circle), restrictor rope based dynamic simulation (triangle), and physical modelling (star). The best fit regression lines are shown each scatter plot.

the towing depth explained approximately 99% of the variation in warp tension in both cases. The warp tension obtained from the dynamic simulation (i.e., 9.9 MT) was significantly lower (31%) than those obtained through the full-scale observations (i.e., 14.3 MT) ($p < 0.05$, Kruskal Wallis test).

3.2. *Comparison between physical modelling and at-sea observations*

Wing-end spread increased linearly with increasing door spread in both physical modelling and full-scale at-sea observations

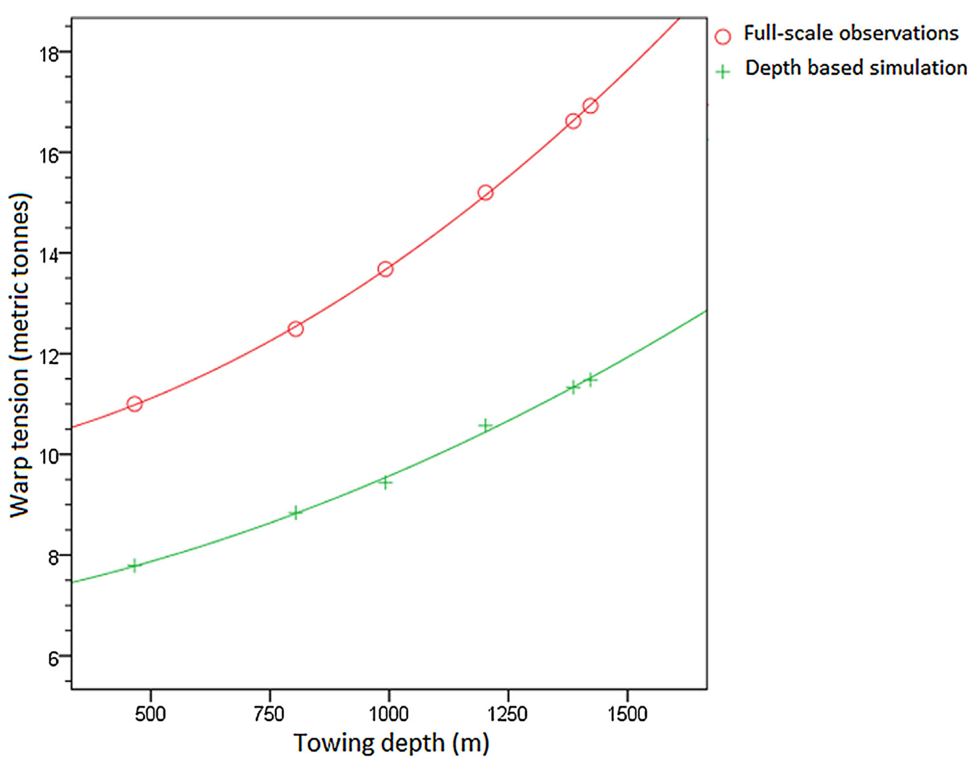

Fig. 5. Relationships observed between warp tension with respect to towing depth. The plots show the experimental data collected with depth based dynamic simulation (plus) and full-scale observations at sea (open circle). The best fit regression lines are shown each scatter plot.

(Fig. 3). Comparison of the data sets revealed the slopes were not statistically different ($p > 0.05$). In both cases, the linear regression analysis explained approximately 98% of the variation in wing spread by changes in door spread. The differences in door spread and wing spread were not statistically significant in the two methods ($p > 0.05$, Kruskal Wallis test).

There was a strong predictive relationship between door spread and headline height in the physical modelling, while there was no clear trend of this relationship for the full-scale observations (Fig. 4). The regression analysis explained adequately the variation in headline height due to changes in door spread for physical modelling ($R^2 = 0.907$), but not the case for the full-scale observations. The headline height predicted by physical modelling was significantly higher (i.e., 14.6%) than that observed during full-scale observations ($p < 0.001$, ANCOVA test).

3.3. *Comparison between dynamic simulation and physical modelling*

Wing-end spread increased linearly with increasing door spread in both the restrictor rope based dynamic simulation and physical modelling, with similar slopes in each case (Fig. 3). However, the mean wing-end spread prediction based on the flume tank modelling was significantly higher (i.e., 6.8%) than the mean obtained from dynamic simulation at a standard speed of 3.0 knots ($p < 0.001$, ANCOVA test). The regression analysis indicates that the door spread and towing speed explained 99% of the variations in wing spread in physical modelling. In dynamic simulation, the door spread explained 99.9% of the variations in wing spread while towing speed did not contribute significantly to the regression model.

Headline height decreased linearly with increasing door spread using both physical modelling and restrictor rope based simulation with the similar slopes in the two methods (Fig. 4). However, the mean headline height predicted using dynamic simulation was substantially lower (i.e., 51.2%) than that which was predicted by physical modelling at 3.0 knots ($p < 0.001$, ANCOVA test). The variation in headline height using the physical modelling was adequately explained by door spread and towing speed ($R^2 = 0.943$) while the headline height was not properly explained by these variables in the dynamic simulation.

Bridle tension showed an increase with door spread using both the restrictor rope based dynamic simulation and physical modelling, albeit with different slopes (Fig. 6a). The fitted relationships intersected at a door spread of 62 m, with predictions of bridle tension diverging at the lower and higher door spreads. Both techniques adequately predicted increasing bridle tension with increasing towing speed (Fig. 6b), with no statistical difference detected between the methods ($p > 0.05$, Kruskal Wallis test). Combined together, our regression analysis indicates that more than 98% of the variation in bridle tension can be explained by door spread and towing speed in the dynamic simulation and physical modelling ($R^2 = 0.980$ and 0.992, respectively).

4. Discussion

This study showed that the use of dynamic simulation and physical modelling provides valuable knowledge regarding the strengths and limitations of each approach and how they could be used to predict the full-scale at-sea engineering performance of bottom trawls. Specifically, we found there was a good agreement between the dynamic simulation and full-scale observations in predicting the main performance parameters of the Campelen 1800 trawl, such as door spread and wing-end spread, but not for headline height and resistance (i.e., warp tension). When comparing physical modelling and full-scale observations, there were generally consistent predictions in terms of door spread, wing-end spread and headline height. Both the dynamic simulation and physical modelling had similar predictions in wing-end spread and resistance (i.e., bridle tension), but not for headline height.

With regard to headline height, our results demonstrated that predictions provided by dynamic simulation (3.0 knots) were significantly lower than those predicted by physical modelling or observed at-sea. Such differences have been commonly recognized by the DynamiT users (K. Zachariassen, pers. comm.; J. Olsen, pers. comm.) as one of the limitations of this simulation software. In contrast, Queirolo et al. (2009) who conducted a comparison between dynamic simulation and model testing of a Chilean trawl design found that the headline height predictions based on the dynamic simulation are higher than values obtained by the flume tank modelling. We speculate that this difference may be related to a difference in the set-up of the simulation and/or a difference in trawl design (Fiorentini et al., 2004). In the current study, the simulations were carried out in which the door spread was artificially constrained at desired distances similar to the way the flume tank operates. This was expected to eliminate biases in trawl geometry performance when comparing the simulation data against model data. The use of a restrictor rope to physically control door spread has been previously investigated for bottom survey trawls (e.g., Campelen 1800 trawl) as a method to reduce variability in door spread with towing depth in order to minimize wing spread variations (up to 25%) and hence reduce variability in resulting estimates of stock abundance (see Engås and Ona, 1991, 1993; Walsh and McCallum, 1996; Fréchet, 2000). In our study, it should be noted that the DynamiT software is normally intended to fully and freely simulate the whole trawling system (B. Vincent, pers. comm.). This is one of the strengths of the numerical approach in that is allows the effects of fishing depth, warps and doors to be simulated (M. Borstad, pers. comm.). Given such advantages of the simulation method compared to physical modelling (i.e., flume tanks do not normally simulate the full trawling system in its working environment), the headline height predicted by the DynamiT without constrained door spread was still seen to be significantly lower (i.e., approximately 45%) than it was predicted by the full-scale-at sea performance. By comparison, differences in headline height between physical modelling and at-sea observations were smaller (14%). We speculate that this difference may be attributed to scale effects, manifested as differences in trawl performance (Christensen, 1973; Hu et al., 2001; Fiorentini et al., 2004). Finally, our observation that the flume tank overestimated headline height compared to full-scale performance is not supported by Morse et al. (1992). The authors found that physical models underestimated headline height observed from full-scale prototypes. This difference may be attributed to a difference in trawl models (Fiorentini et al., 2004).

The tendency of door spread and wing-end spread to increase with towing depth has been recognized in other studies (see Walsh and McCallum, 1996, 1997; Fréchet, 1996; McCallum and Walsh, 1999; Bertrand et al., 2002). The results from our dynamic simulation of the Campelen 1800 trawl support this phenomenon, however no such trends were observed for our full-scale observations. While the depth range was more than sufficient, we suspect our sample size may have been too small to statistically detect a relationship. This type of data has been shown to be inherently variable (e.g. Walsh and McCallum, 1997; Bertrand et al., 2002) and increasing the sample size may have improved model fit.

With regard to predicting the drag of a trawl, both dynamic simulation and physical modelling demonstrated good agreement in predicting the bridle tension (or net drag). This finding is not consistent with the results from Queirolo et al. (2009) who documented a considerable difference (i.e., 13–23%) using the two methods. The different results between these two studies may be explained by

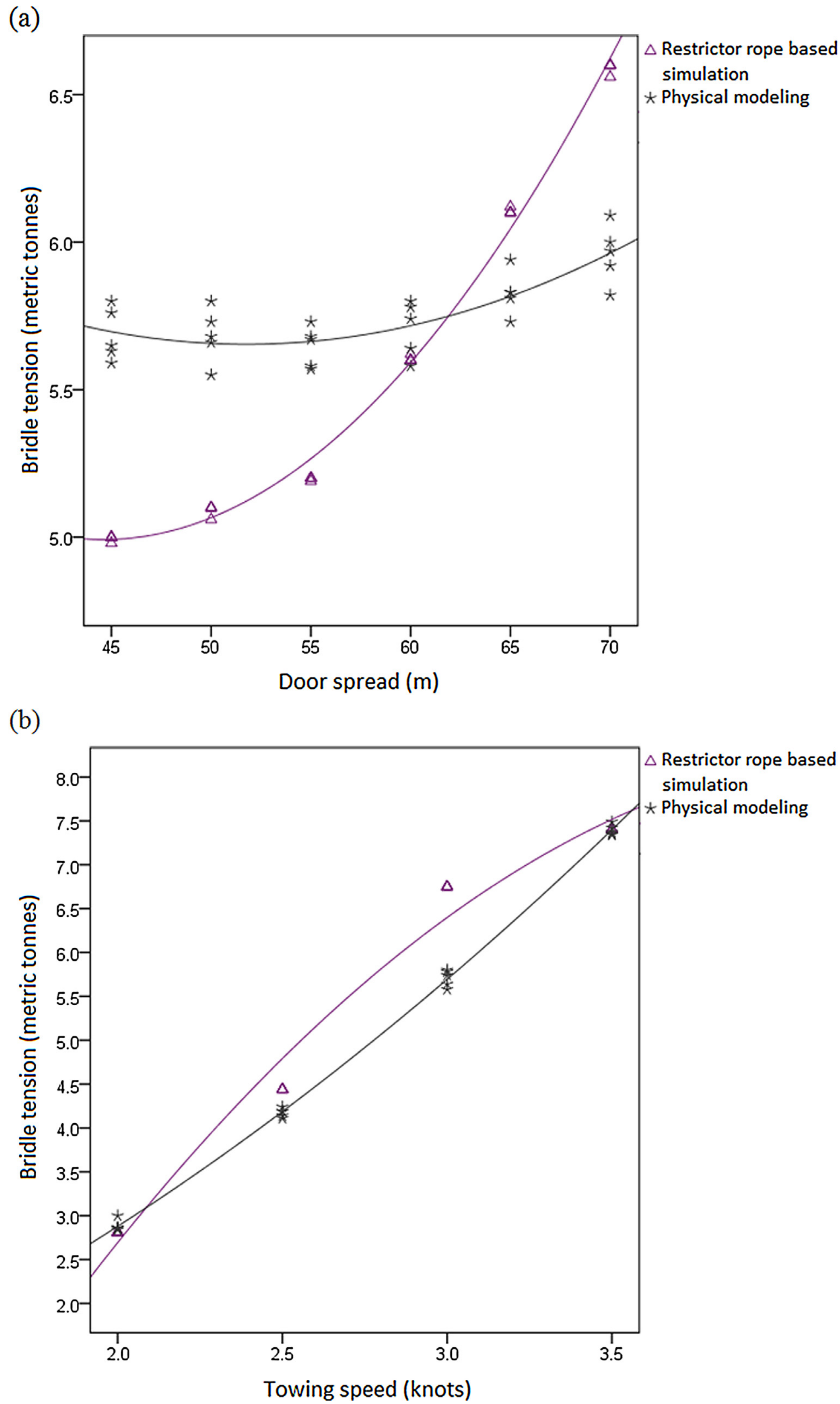

Fig. 6. Relationships observed between bridle tension and door spread (6a); bridle tension and towing speed (6b). The plots show the experimental data collected with dynamic simulation (triangle), and physical modelling (star). The best fit regression lines are shown each scatter plot.

the differences in how a simulation was set up and conducted. In the case of warp tension (or total drag) in our study, a significant difference was observed between the simulation testing and full-scale observations. There are different factors that could be attributed to this difference. In real fishing conditions, drag measurements will contain uncertainty due to natural variation in oceanographic conditions (e.g., current, wind, swell) (Fiorentini et al., 2004; Sala et al., 2009). By comparison, the resistance (i.e., warp tension) predicted by dynamic simulation must be considered carefully with caution. For example, there is no spreading effect of the trawl doors due to its shearing effect with the substrate because of no relief of the sea floor. In addition, the trawl gear does not affect the fluid flow and is towed in still water. Moreover, the footgear height is not simulated with a high degree of fidelity (e.g., diameter and spacing of rubber disks). In fact, the drag regarding trawl door and footgear components and/or their operational contact with the seabed (e.g., penetrating into the seafloor) normally forms a significant drag component of the whole trawling system. These limitations of the dynamic simulation method could potentially to explain why the drag measurements obtained in the dynamic simulation tended to be lower (or different) than of the full-scale observations at sea.

In conclusion, all of the methods used in this study have their own weakness and merits. The ideal method with which to accurately predict full-scale at-sea performance of bottom trawls or used for designing a trawling system probably does not exist. The precision and accuracy of the predictions depends on many factors. Whichever method is employed, thoroughness and care must be emphasized in order to reduce bias in predicted values. The choice of method will be largely determined by the specific purposes of a design/experiment and the financial and material resources available. For example, a simulation tool should be used for assessing the relative effect of a gear modification to a trawling system (e.g., modify a length, floatation, twine diameter, mesh size, etc.) at an affordable cost. Whereas, physical modelling in a flume tank is best designed for investigating the effects of rigging and modification changes on gear behaviour and performance visually and in a direct way. Therefore, the importance of using two or three complementary tools should be considered as the ideal process for designing a trawling system and/or assisting the gear development circle.

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